Status of R&D on Calorimetry for EIC

The EIC Calorimeter R&D Consortium (eRD1)

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EIC R&D Committee Meeting

January 28, 2015

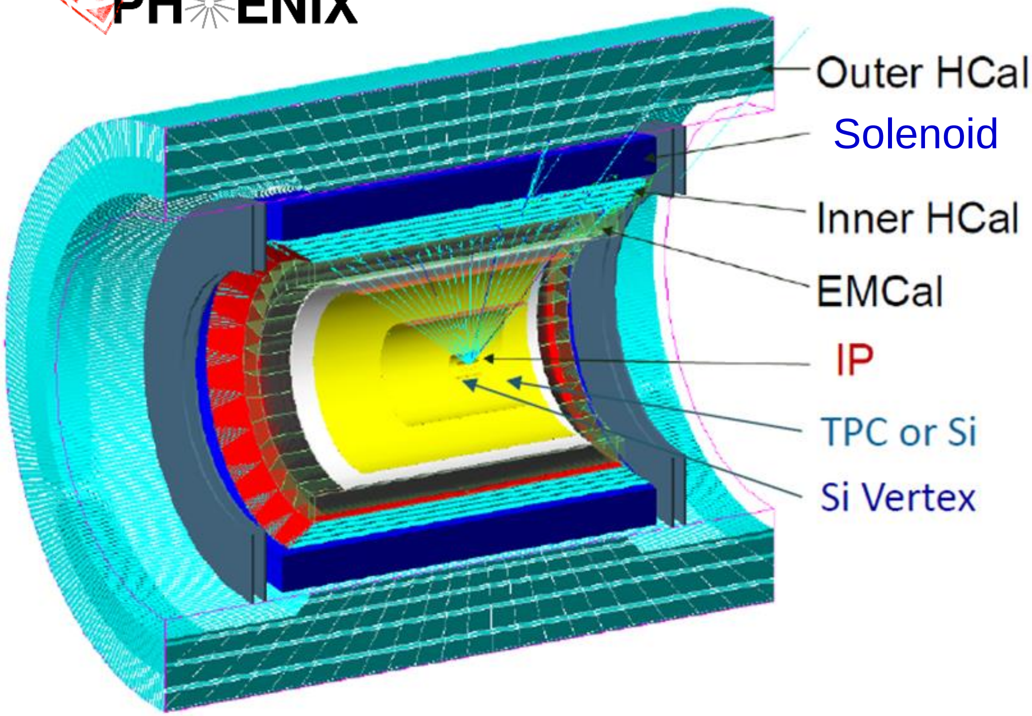
Progress Reports

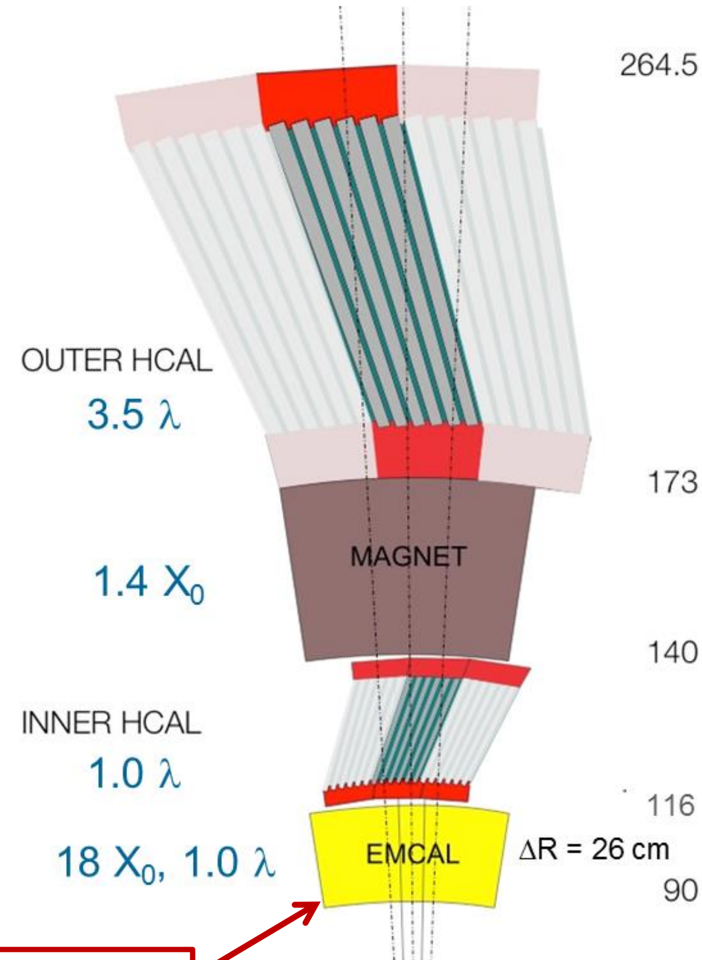
January 2016

- Development of tungsten powder epoxy scintillating fiber electromagnetic calorimeters (W/SciFi SPACALs)
  - BNL, UIUC, UCLA, IU
- Development of $PbWO_4$ for a forward EMCAL at EIC
  - CU/JLAB, Orsay, Caltech, BNL
- Study of radiation damage in SiPMs
  - BNL (PHENIX), UCLA (STAR)
- Monte Carlo simulations
  - Mainly BNL

Development of W/SciFi SPACAL Modules for sPHENIX

Note: This R&D is being funded almost entirely out of PHENIX R&D funds !



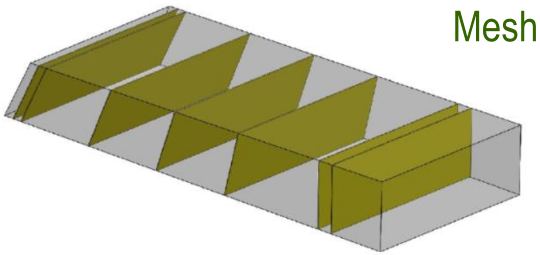


EMCAL + HCAL ~ 5.5 λ

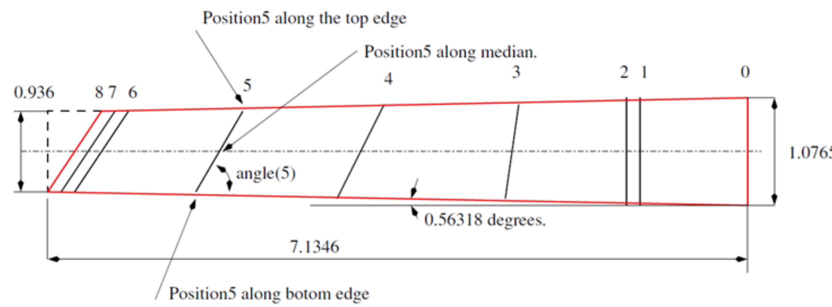
W/SciFi SPACAL : ~ 25K towers

1D Projective Modules

Design developed at UCLA can be projective in ϕ or η but not both



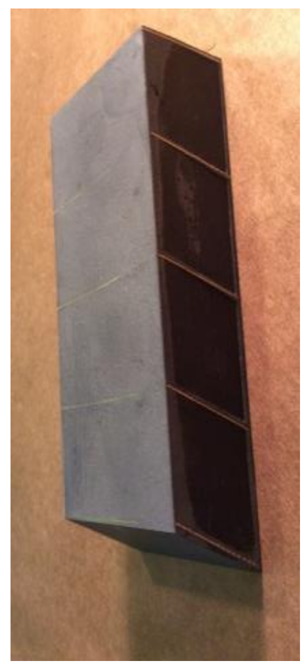
Mesh screens



Modules produced at BNL, UIUC and THP

BNL

UIUC



THP Tungsten HEAVY Powder, Inc.

Mass Production of Absorber Blocks

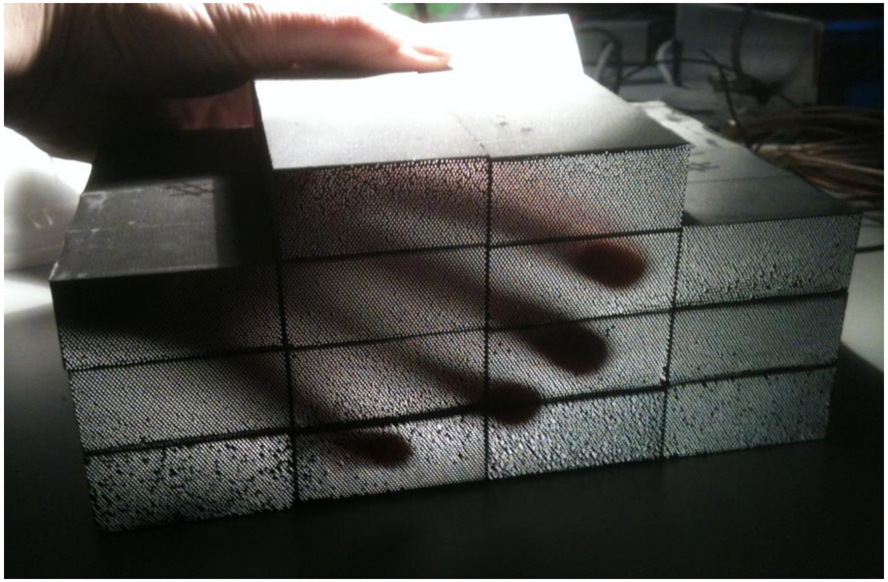
Require 25K towers for the entire calorimeter

Tungsten HEAVY Powder, Inc.

Supplier of tungsten powder

- Developing a mass production technique for producing blocks
- Use a centrifuge method for achieving density > 10 g/cm^3
- Density variation within module < 1%
- Currently making 16 for prototype

University of Illinois Urbana Champaign

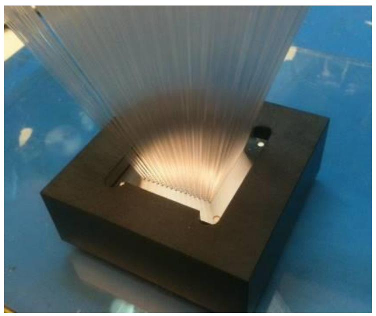


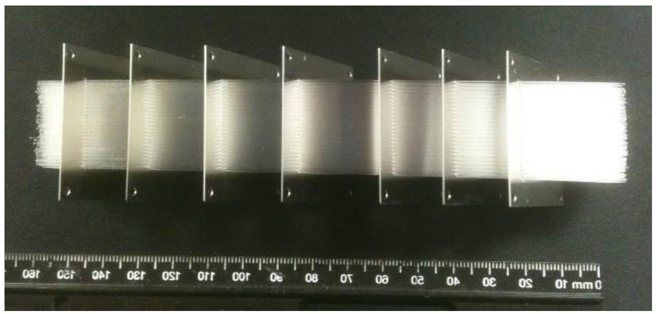
- UIUC is also developing procedures for producing large numbers of blocks
- 16 blocks produced so far for next prototype

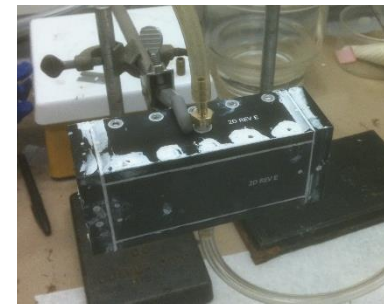
2D Projective Modules

Projective in ϕ and η with different tapers in both projections

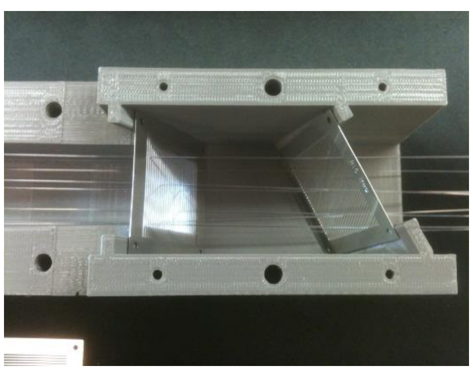
Tapered Hole Meshes: Uses a series of meshes with conical shaped holes, each with a slightly different hole spacing, to position the fibers

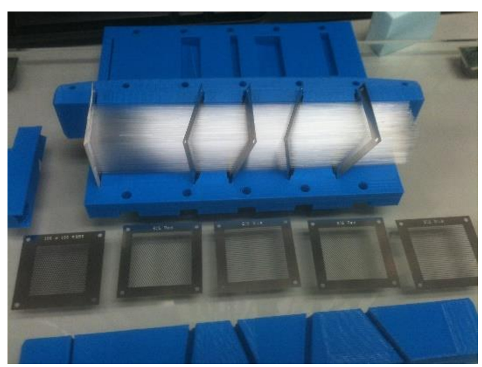


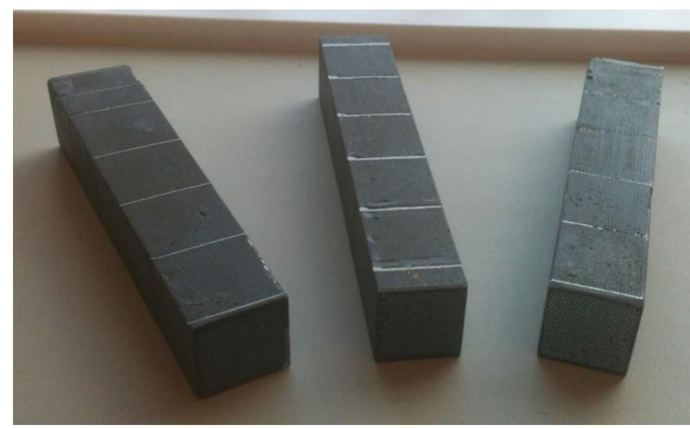




Tilted Wire Frame: Uses a series of angled wire frames to taper the array of fibers inside the tower





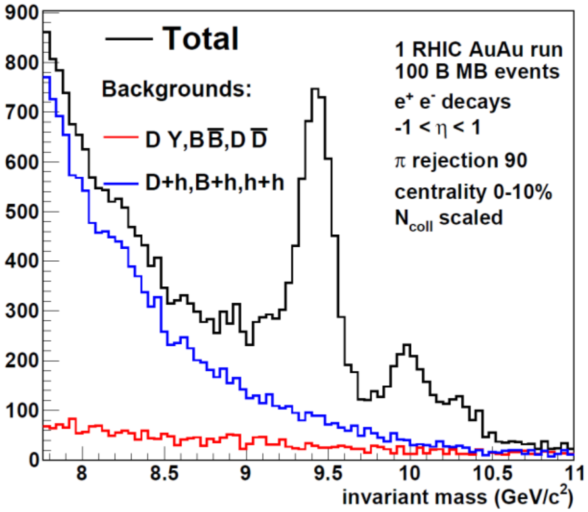


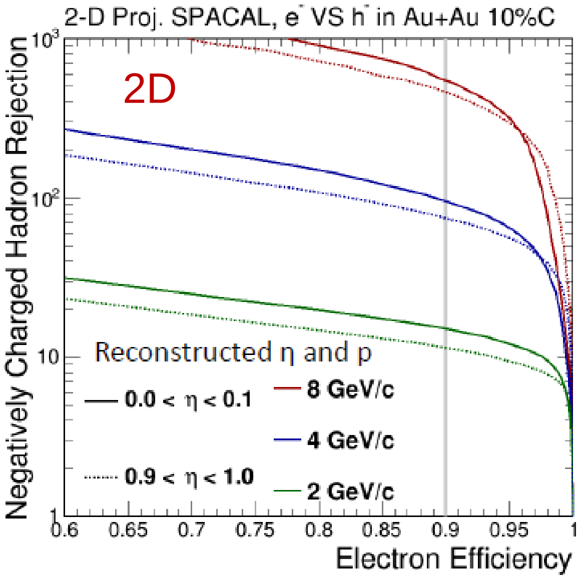
First 2D tapered SPACAL modules produced at BNL

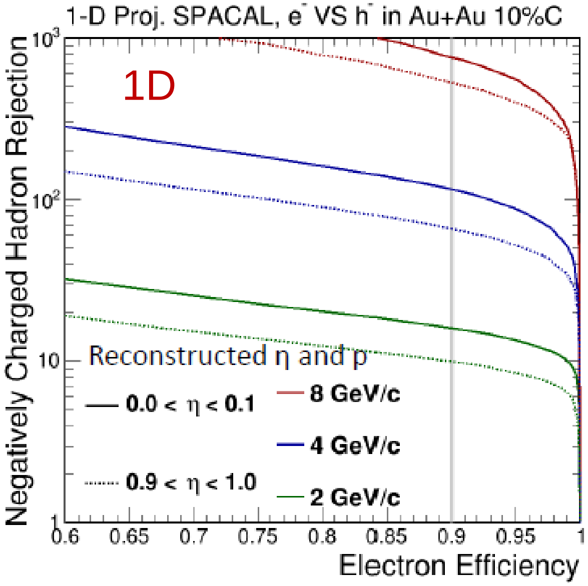
Why 2D Projective Modules ?

In sPHENIX, due to the high multiplicity in central heavy ion collisions, having a fully (2D) projective calorimeter improves electron id at large η

Requires hadron rejection ~100:1 with high electron efficiency (~ 90%) to identify Υ 's







J. Huang (BNL)

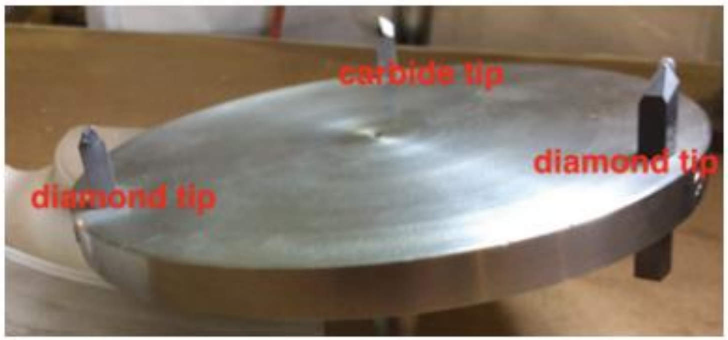
Electron ID looks marginally adequate with 1D projective but with little or no safety margin

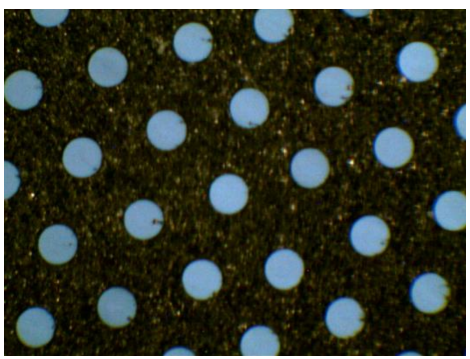
More MC calculations are currently under way !

Finishing of Module Ends

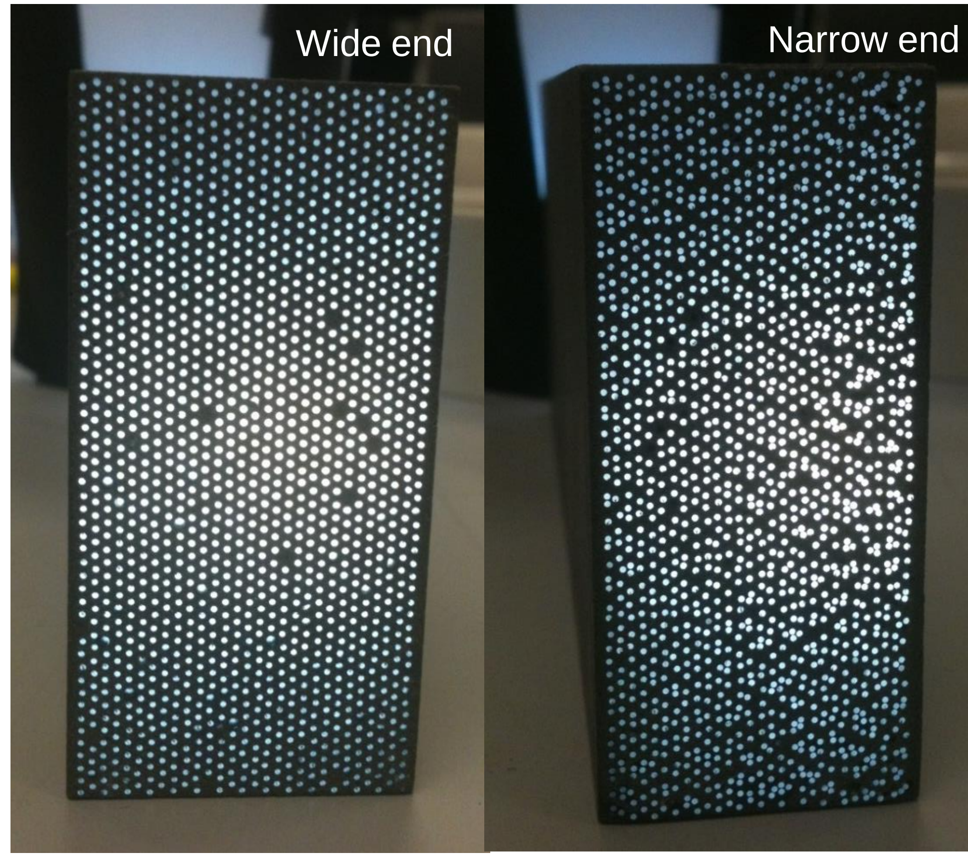
Need polished finish on fiber ends to have good light collection on readout end and high reflectivity on opposite end

Diamond Fly Cutter at UIUC





Ends are fly cut as a last machining step and do not need further polishing

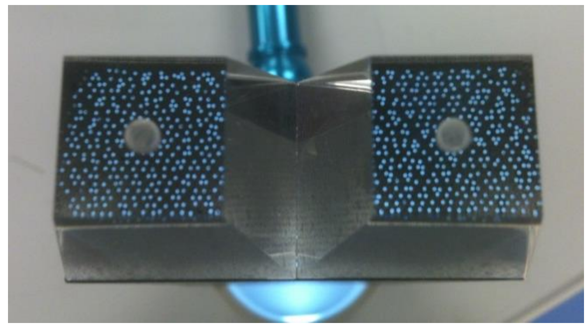


Fibers at narrow end are not fully supported by meshes in current design. Will be corrected on next iteration

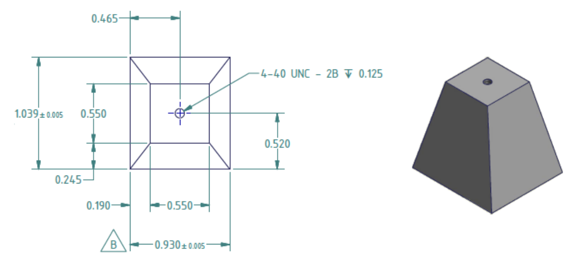
Light Collection and Tower Segmentation

- Short light guide is used to collect light from tower

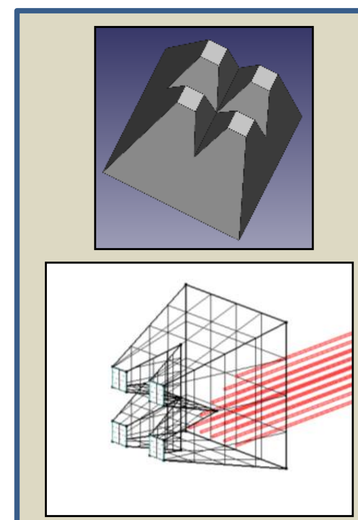
  Tower (24 mm x 24 mm = 576 mm^2) $\rightarrow$ 4 SiPMs (4 x 9mm^2 = 36mm^2) $\Rightarrow$ ~ 6%
- Present design will use an acrylic trapezoidal pyramid shape



- Light collection efficiency ~ 70% for complete coverage of readout end (e.g., PMT)
- Efficiency with 4 SiPMs ~ 30%



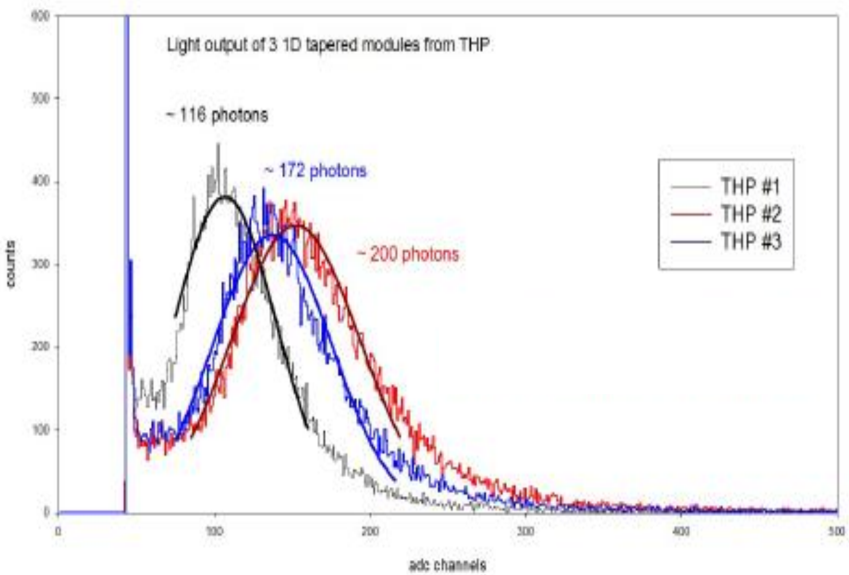
Monte Carlo simulations are ongoing to improve the design and light collection efficiency



Light Yield

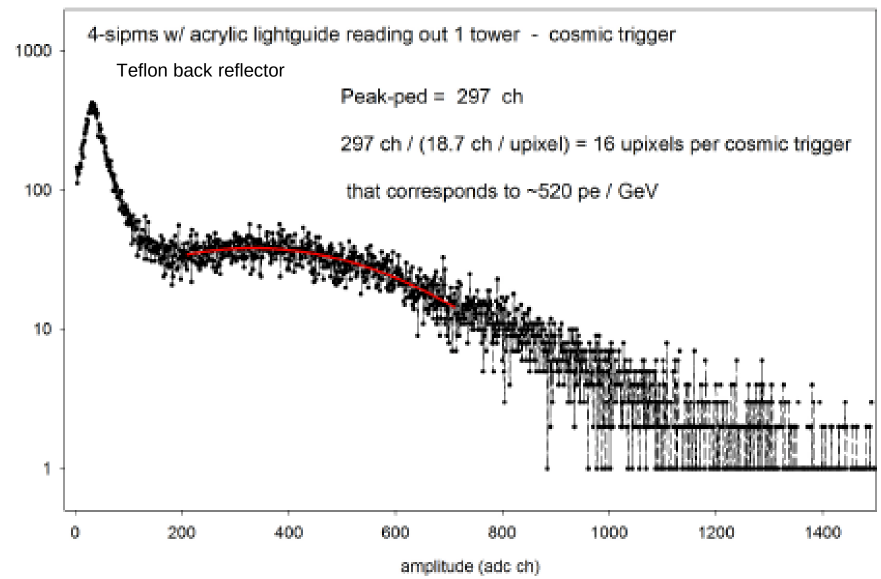
Measured light output of THP blocks with cosmic rays traversing module transversely (E_{dep} ~ 30 MeV)

PMT with full coverage of readout end



Can see improvement in THP modules over time

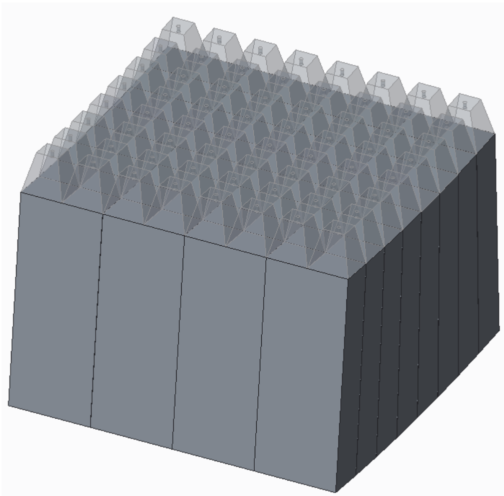
Readout with light guide and 4 SiPMs



Consistent with UCLA beam test measurement of ~ 500 p.e./GeV

W/SciFi Prototype

8x8 tower prototype to be tested with sPHENIX HCAL prototype in April 2016

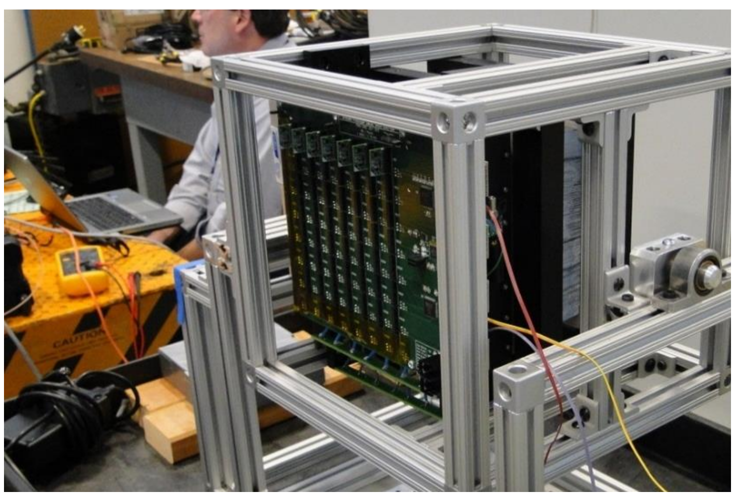


8x8 tower array of
1D projective 1x2
tower blocks

16 blocks from THP
16 blocks from UIUC

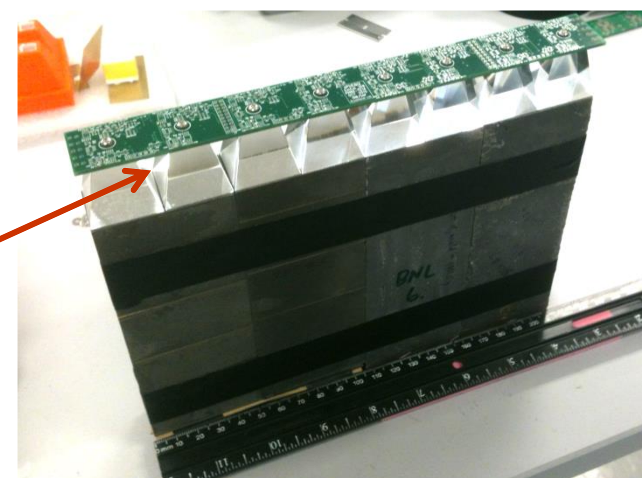
Module of 1x8 row of towers

Preamp board (4 SiPMs per tower)



Support frame from earlier prototype

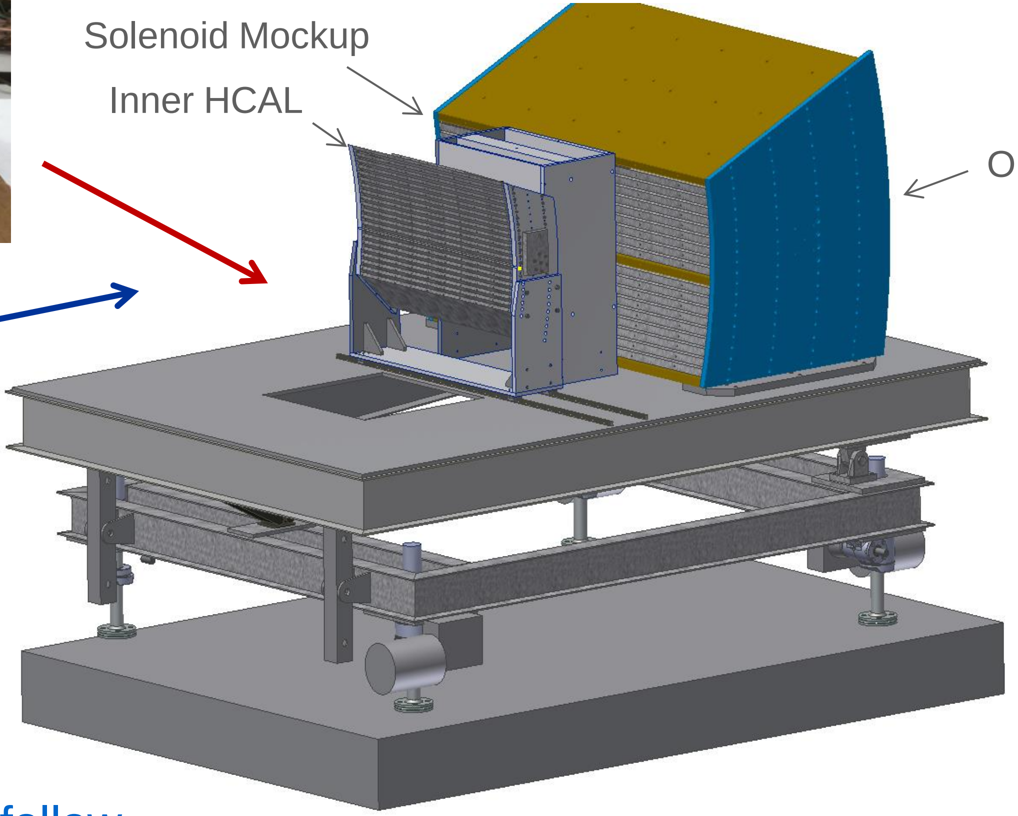
LEDs for calibration



Fermilab Test Beam – April 2016

8x8 tower EMCAL prototype

sPHENIX HCAL prototype
Inner + Outer
4x4 towers each



e,h$^{\pm}$

sPHENIX test
April 6 – May 3

Test of HR SPACAL will follow
May 4-10

Calorimeter R&D at UCLA

- Backward EMC (BEMC) (e-direction)

  Design aims at high energy resolution (~ 6-7%/√E) for electron measurement

  Goal: Determine limit on intrinsic resolution and evaluate if this technology is viable for a High Resolution SPACAL in the e-going direction

  - Rework existing prototype (W/Sn absorber) at UIUC. Change to a single PMT readout with light guide to measure total light output.
  - Boost light yield and apply compensation from the back end for better uniformity (instead of filter at readout end)
  - Build a new prototype with thicker fibers and only W absorber (also read out with light guide + PMT)
  - Test both prototypes at FNAL

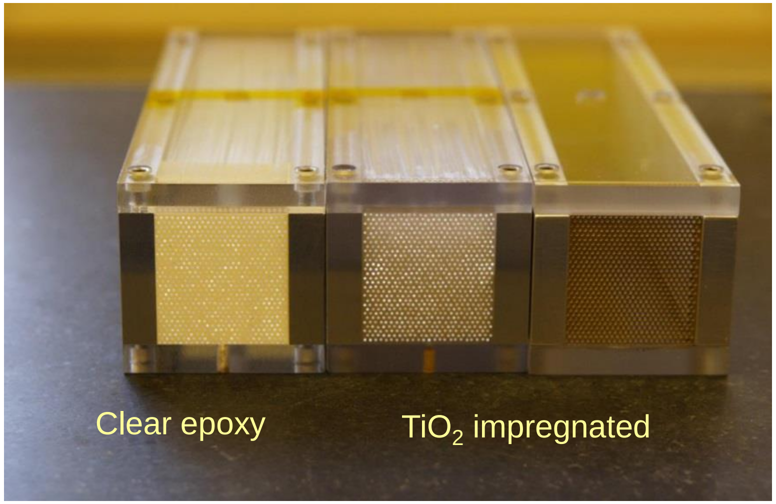
- Forward EMC (FEMC) (h-direction)

  Goal: Build a prototype detector with Kuraray radiation hard 3HF fibers and optimized for APDs

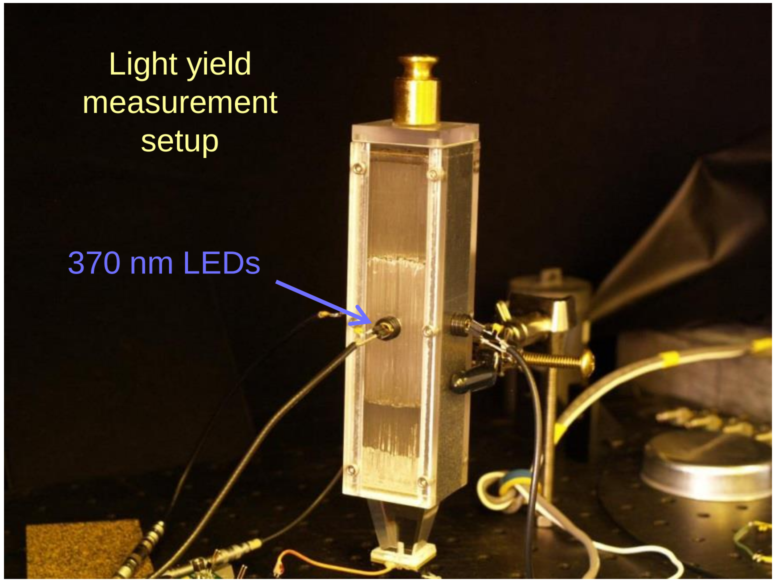
  - Stopped this development due to lack of funding and the fact that the light yield of 3HF fibers was too low (~22% of Kuraray SCSF78 fibers).

- Study readout sensors (SiPMs vs APDs)
  - Quantify rate of anomalous signals for SiPM and APD based readouts

Reflector Studies and Light Yield Measurements



Fibers with different end finish



End mirror studies (% increase compared with no reflector)

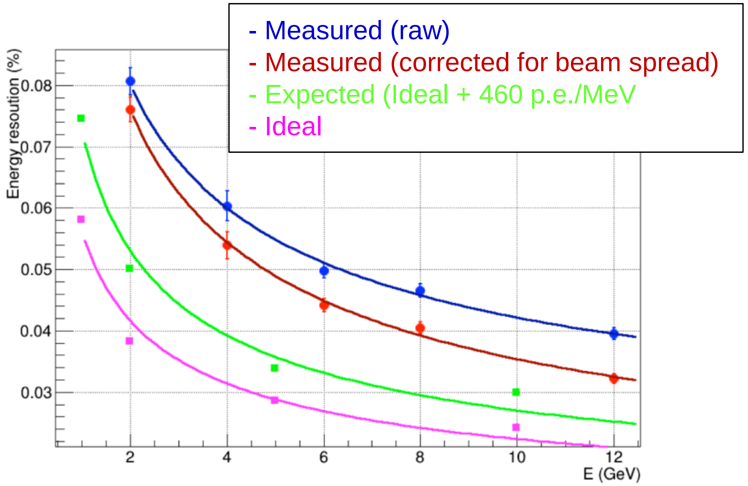
Polished far end:

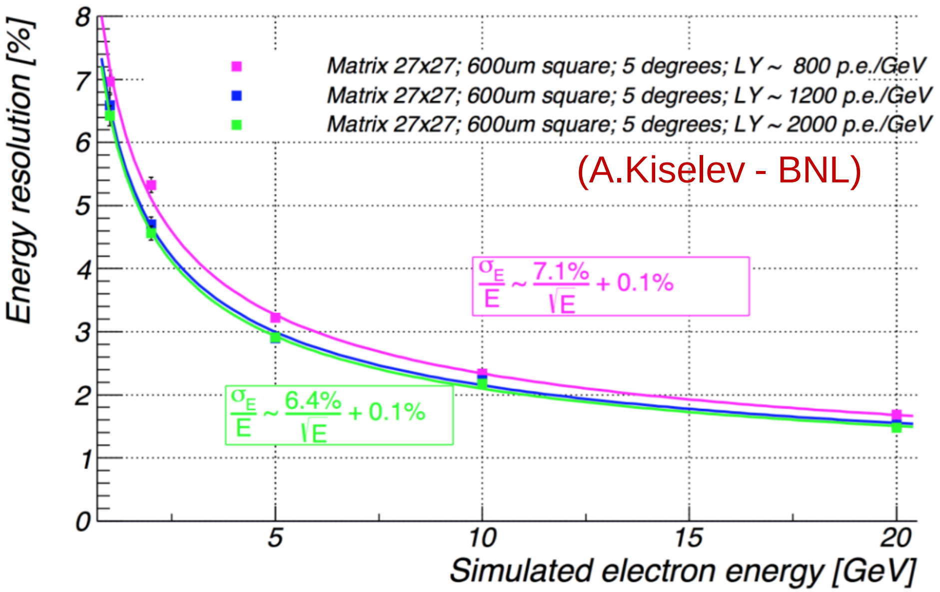
- ESR - 70% (same as 2012 result)
- Aluminized acrylic mirror – 65%
- White diffuser – 22%

Abraded far end:

- Aluminum - 35% (not polished)
- Aluminized acrylic mirror – 45%
- White diffuser – 15%

Revised Design of High Resolution Prototype





Initial design (tested May 2015):

- W/Sn absorber
- Gave worse resolution and lower light yield than expected
- Possible causes:
  - mechanical damage to fibers during fabrication
  - non-uniformities in absorber composition
  - imperfections in filter used for light compensation
- End surfaces of all modules were re-machined and fly cut finished at UIUC

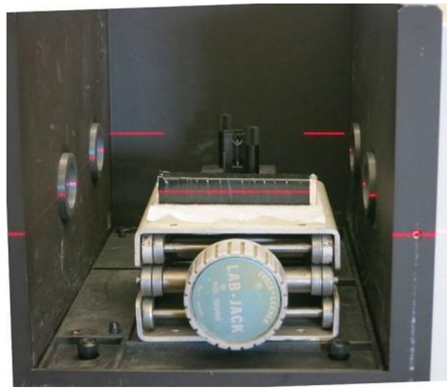
Revised design (guided by MC simulation):

- Decrease sampling frequency (larger spacing)
- Increase sampling fraction (thicker fibers)
- Round fibers → square fibers (better packing)
- W/Sn powder → W powder (better uniformity)

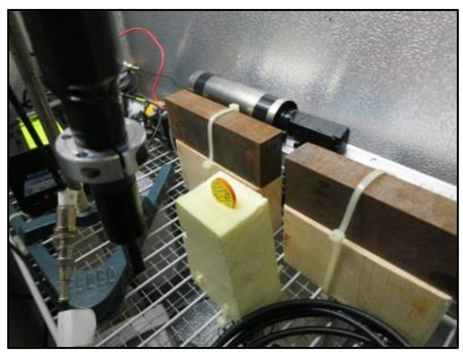
Test of both HR prototypes planned for May 2016 at Fermilab

Progress on R&D on PbWO4 Crystals

New Infrastructure at CUA and Orsay (supported by institutional funds)



Optical transmittance measurement setups at CUA and IPN-Orsay



Temperature-controlled dark box (left) and setup for light yield measurements (right)

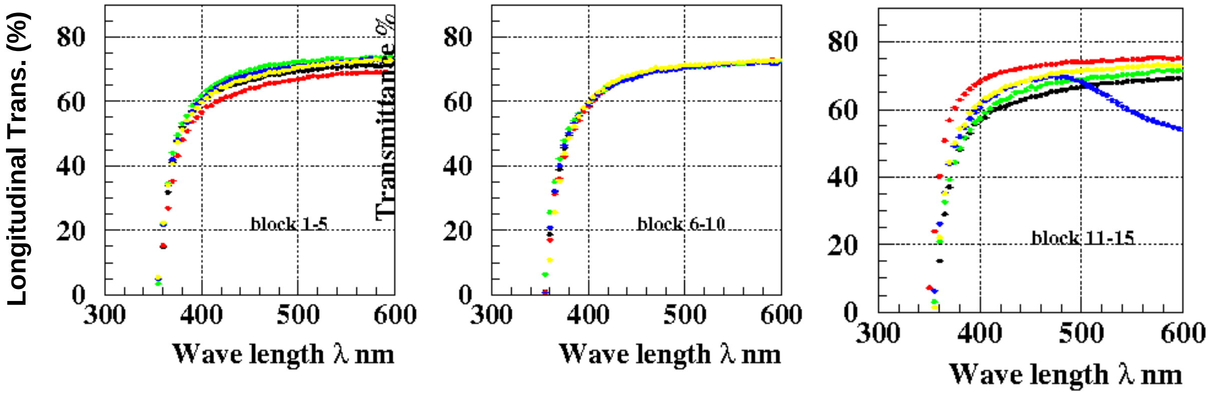
Vitreous State Laboratory at CUA has joined the effort

Capabilities:

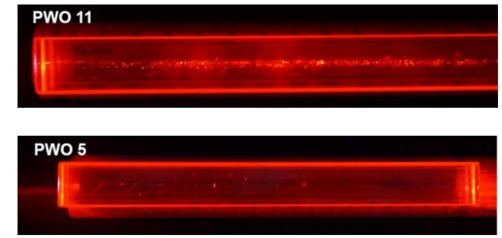
- X-ray irradiators and a wide spectrum of radioactive materials licenses
- Wide array of temperature-programmable furnaces (room temperature to 1600 °C)
- X-ray diffraction
- X-ray fluorescence spectroscopy, optical-UV absorption spectroscopy
- Scanning electron microscopy with energy dispersive x-ray spectroscopy and wavelength dispersive x-ray spectroscopy
- Transmission electron microscopy with energy dispersive x-ray spectroscopy and wavelength dispersive x-ray spectroscopy
- Numerous optical microscopes
- Raman microscope with multiple excitation wavelength
- Thermogravimetric analysis, differential scanning calorimetry, differential thermal analysis, thermal conductivity, heat capacity/Density
- Crystal cutting and polishing facilities, vacuum coating facilities
- Extensive chemical analysis (ICP-MS, ICP-ES, DCP-ES, MS, GC, IC, XRF, FT-IR)

SIC Crystals

SIC crystals produced in 2014 (measured at JLAB)

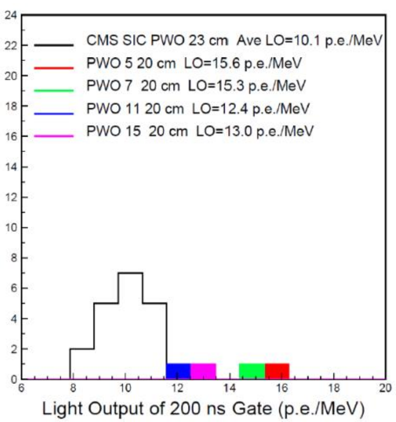


Some samples show significant scatter

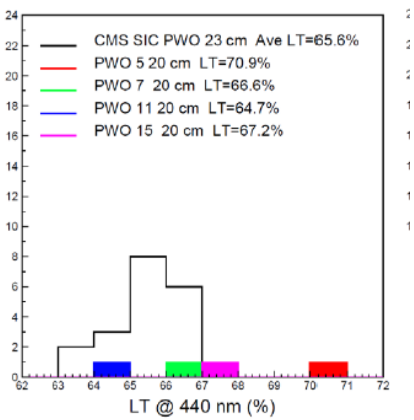


Comparison with CMS crystals (measured at Caltech)

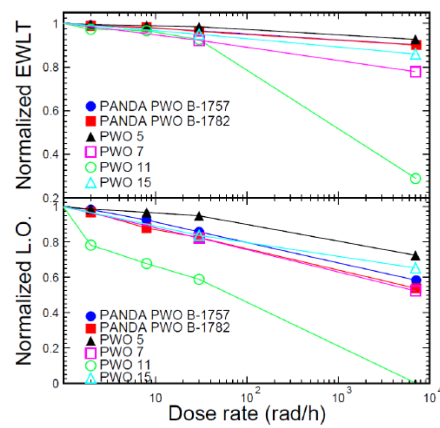
Light output



Longitudinal Transmittance



Radiation damage



- Light output and longitudinal transmittance of some samples are higher than CMS crystals.
- Some samples show better radiation hardness, some are comparable, and some are worse

However, there are still significant sample to sample variations

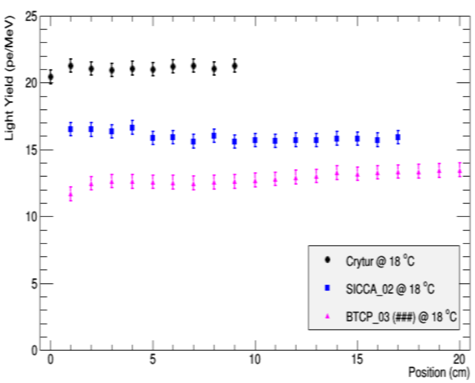
New crystals produced in 2015 are currently being studied

Crytur Crystals

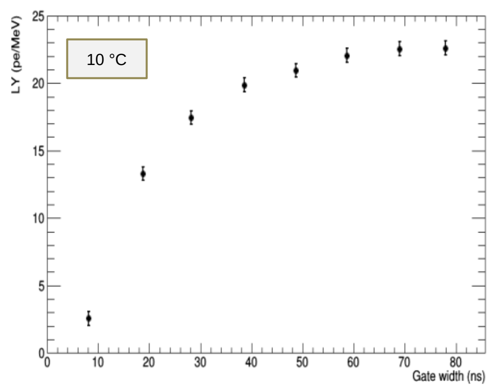
New Infrastructure at Crytur for producing large crystals

Aimed mainly at PANDA

10 cm long crystal (2015)

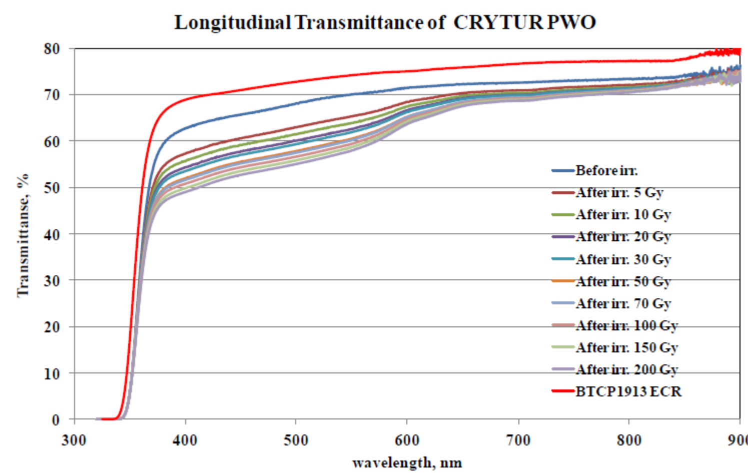


Light output compared to 20 cm long crystals produced by SICCAS in 2014 and BTCP.



Light output vs integration time.

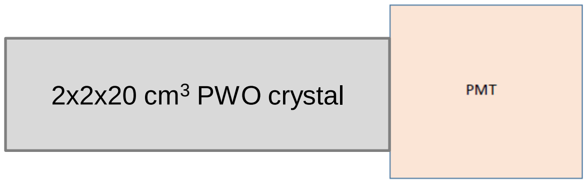
20 cm long crystal (2015)

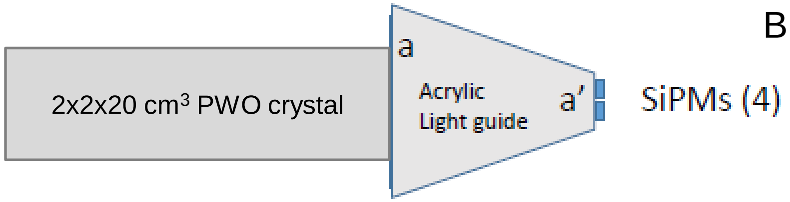


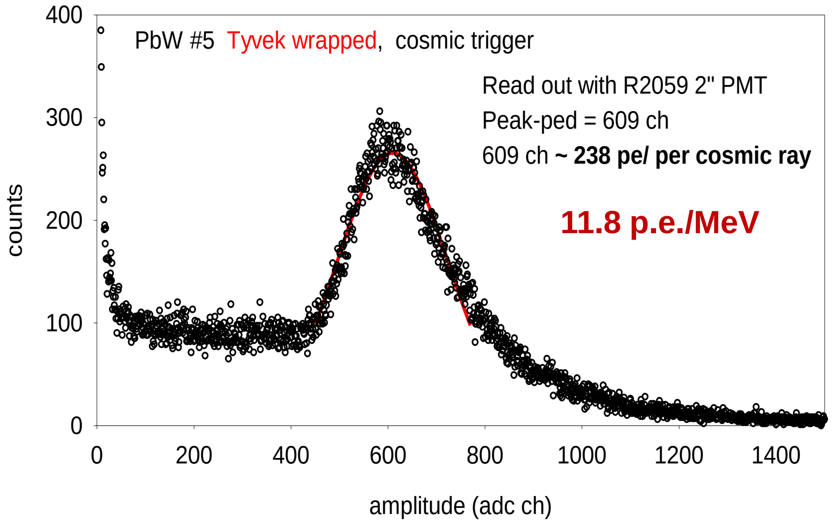
Courtesy of R. Novotny (PANDA)
2015 IEEE NSS/MIC

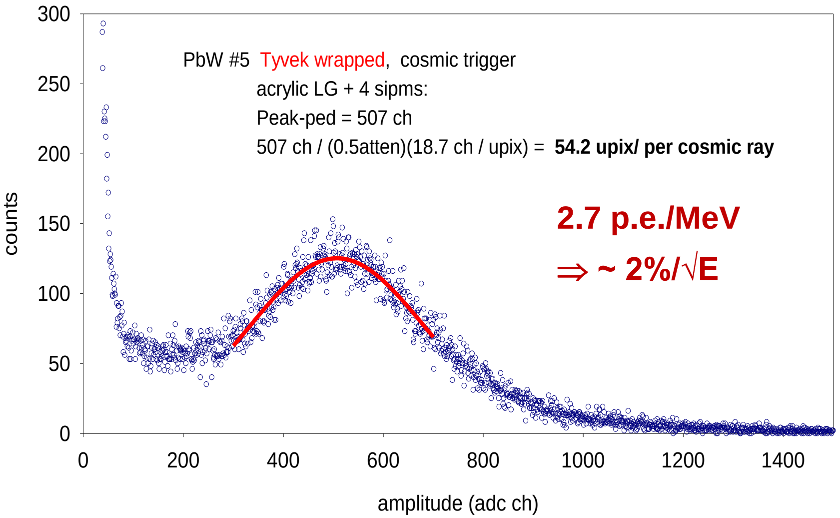
PWO Crystal Readout with SiPMs

S.Stoll
BNL









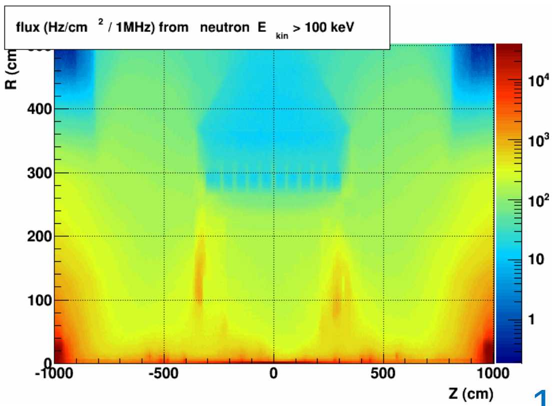
Pulse height spectrum for SIC crystal #5 measured with a PMT with full photocathode coverage of the readout end of the crystal.

Pulse height spectrum for SIC crystal #5 measured with cosmic rays using 4 Hamamatsu S-12572-015P SiPMs and a 1" acrylic light guide

Agrees reasonably well with expected light collection efficiency with light guide and SiPM area coverage

Radiation Damage in SiPMs

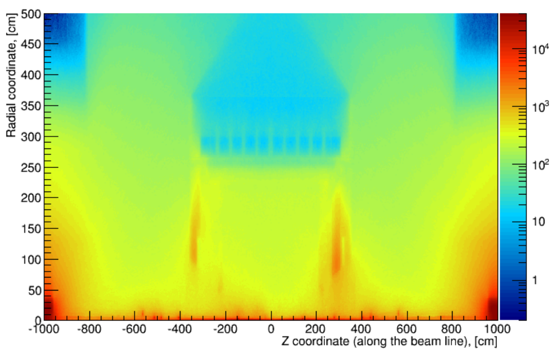
New calculation to estimate neutron fluences in BeAST Detector



Neutron flux above 100 KeV per 10^6 PYTHIA events

STAR
(Y.Fisyak)

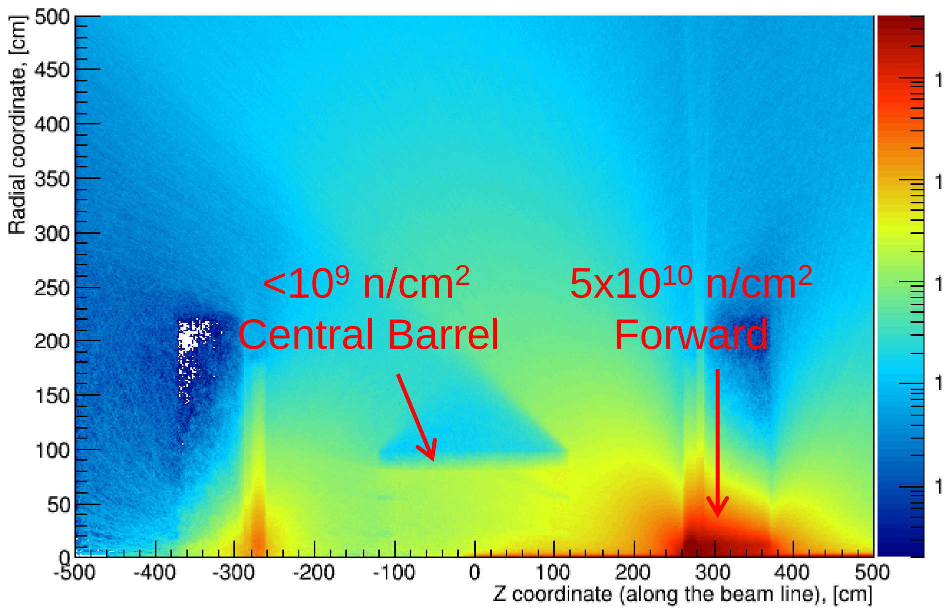
100x100 GeV pp



EICRoot
(A.Kiselev)

Calculations verified for STAR 2014 detector configuration

20x250 GeV ep (100 days)

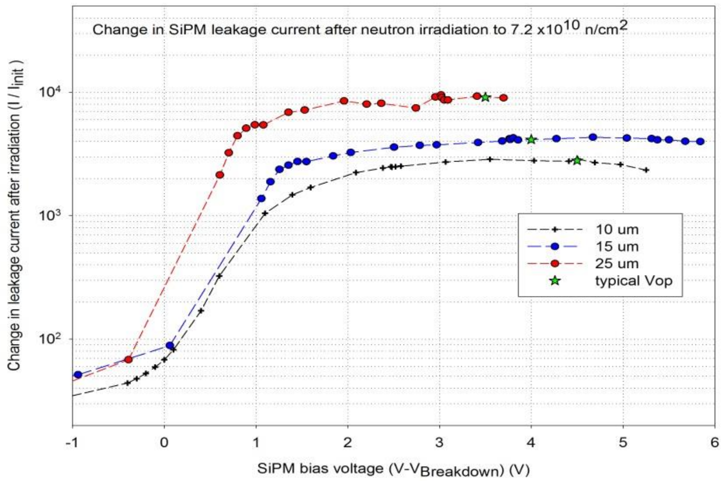


Model of BeAST detector in STAR Hall w/o beam line elements and no return yolk

These ***very preliminary*** results indicate that the neutron fluences at EIC may be lower than those observed at RHIC

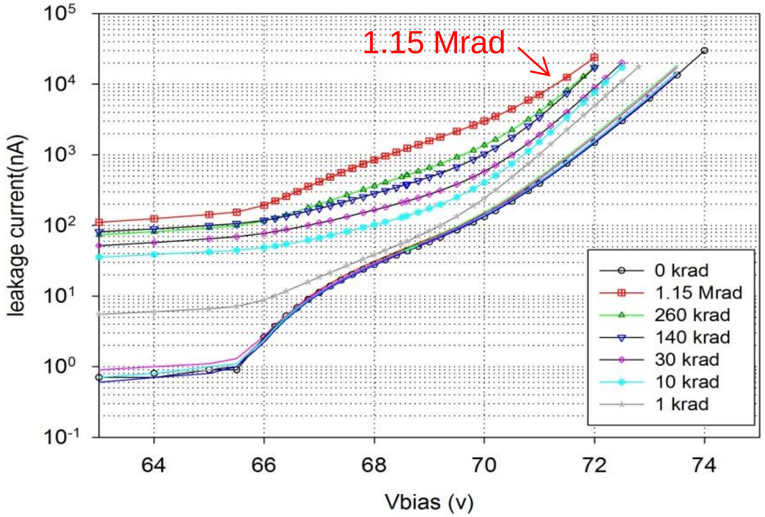
Radiation Damage with Neutrons and Gammas

Neutrons



Relative increase in dark current with bias voltage for three different pixel size devices after exposure to 7.2 x 10^{10} n/cm^2 at LANSCE.

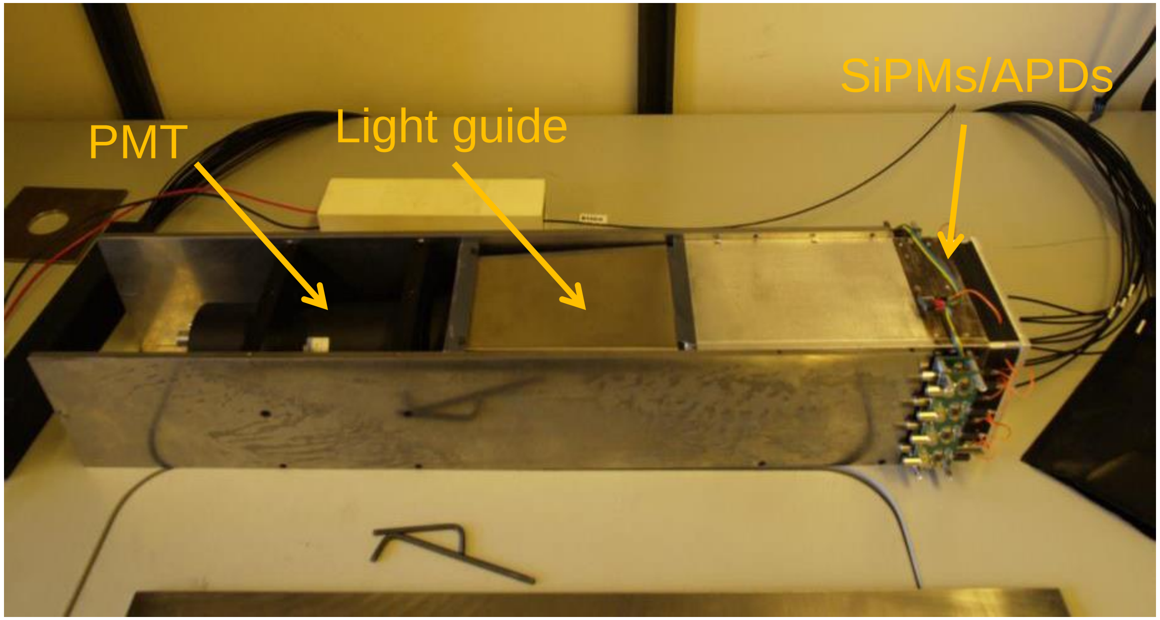
Gammas



Change in dark current for Hamamatsu S12572-015P 15 μm pixel SiPMs for increased exposures to ^{60}Co gamma rays at the Gamma Ray Irradiation Facility at BNL.

- Smaller pixel devices show less damage than larger pixel devices
  New 15 μm devices from Hamamatsu have same PDE (25%) as old 25 μm devices ⇒ good compromise
- Damage due to gammas is observable but much less than for neutrons

IR Tests planned for Run 16



BEMC module with SiPM/APD and PMT readouts
to be tested in STAR during Run 16

Will study effects of radiation damage in SiPMs and Nuclear Counter Effect in APDs

PHENIX will also test a SPACAL module with a complete SiPM
readout system in the PHENIX IR during Run 16

Publications and Talks

Publications:

1 Journal of Physics: Conference Series 404 (2012) 012023 O. D. Tsai, et.al. ‘Results of R&D on a new construction technique for W/ScFi Calorimeters’ Talk at CALOR 2012.

2. NIM A 756(2014) 68-72 Y. Fisyak et.al.’ Thermal neutron flux measurements in the STAR experimental hall’.

3. Journal of Physics: Conference Series 587(2015) 01205 O. D. Tsai, et.al., ‘Development of a forward calorimeter system for the STAR experiment’ Both test beam results for the STAR forward calorimeter system and EIC barrel EMcal were presented in a single talk at CALOR 2014.

4. Journal of Physics: Conference Series 587(2015) 011001, C.Woody and E.Kistenev, “Design Studies of the Calorimeter Systems for the sPHENIX Experiment at RHIC and Future Upgrade Plans”, Proceedings of CALOR 2014 International Conference on Calorimetry in High Energy Physics (included EIC calorimeter R&D)

Talks:

1. "R&D on a new construction technique for W/ScFi calorimeters", O.Tsai (UCLA), CALOR 2012, Santa Fe, NM, June 2012
2. "Technology Choices for the sPHENIX Calorimeter Systems", C.Woody (BNL), CALOR 2012, Santa Fe, NM, June 2012 (included EIC calorimeter R&D)
3. "The Calorimeter Systems for the sPHENIX Experiment at RHIC", C. Woody (BNL), 2012 IEEE NSS/MIC, Anaheim, CA, October 2012 (included EIC calorimeter R&D)
4. "Design of the Electromagnetic and Hadronic Calorimeters for the sPHENIX Experiment at RHIC", C. Woody (BNL), 2013 IEEE NSS/MIC, Seoul, Korea, October 2013 (included EIC calorimeter R&D)
5. "Development of a Forward calorimeter system for the STAR experiment", O.Tsai (UCLA), CALOR 2014, Giessen, Germany, April 2014 (test beam results for EIC barrel EMcal presented in the same talk).
6. "Design of a New Electromagnetic Calorimeter for the sPHENIX Experiment at RHIC", C. Woody (BNL), CALOR 2014, Giessen, Germany, April 2014 (included EIC calorimeter R&D)
7. "Results of R&D for sampling calorimeters for EIC", O.Tsai (UCLA), EIC Users Meeting, Stony Brook University, June 2014
8. "Results of R&D for sampling calorimeters for EIC", O.Tsai (UCLA), 2014 IEEE NSS/MIC, Seattle, WA, November 2014
9. "Crystal Calorimeter R&D for the Electron Ion Collider", T. Horn (Catholic University of America), SCINT 2015, Berkeley, CA, June 2015
10. "Calorimetry detector R&D", J. Huang (BNL), EIC Users Group Meeting, Berkeley, CA, Jan 2016

Students

1. W. Xu (UCLA)
2. L. Dunkelberger (UCLA)
3. K. Ladry (UCLA)
4. Y.X. Pan (UCLA)
5. A. Lamson (RPI)
6. M. Sergeeva (UCLA)
7. A. Ruckel (UCLA)
8. C. Dilks (PSU)
9. F.Georges (IPN-Orsay)
10. S. Ali (CUA)
11. M.Carmignotto (CUA)

Expected Future Funding Requests (FY17)

Investigation Area	Amount	Comments
W/SciFi SpaCal	~ $125K	Development of HR SPACAL and methods for module mass production
Radiation damage studies on sensors (SiPMs and APDs)	~ $50K	Includes some new electronics development
PWO R&D	$75K	Crystal procurement from Crytur and radiation damage studies (carryover from FY16)
Total	**$250K**	

Summary and Future Plans

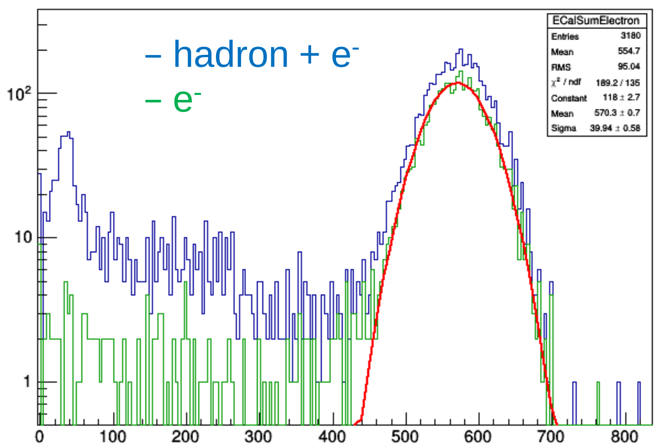
- Considerable progress made on producing SPACAL modules at other university labs and in industry
- Procedure has been developed for producing 2D SPACAL modules which should be adaptable to the same type of production methods as 1D modules
- New High Resolution SPACAL design has been developed
- Both standard resolution and high resolution SPACAL prototypes will be tested at Fermilab in Spring of 2016
- Considerable progress has been made at Crytur for producing PWO, lead mainly by PANDA. However, we need to have our own EIC involvement with this effort.
- PWO crystals from SIC still show variability and needs further study
- Very preliminary studies of neutron fluences at EIC seem lower than previously expected, but further studies are needed, as well as additional radiation damage studies with SiPMs and APDs.

Backup Slides

Comparison of Test Beam Data with Monte Carlo

J. Huang (BNL)

Implemented complete 2014 UCLA test beam geometry in GEANT4 (down to individual fibers)

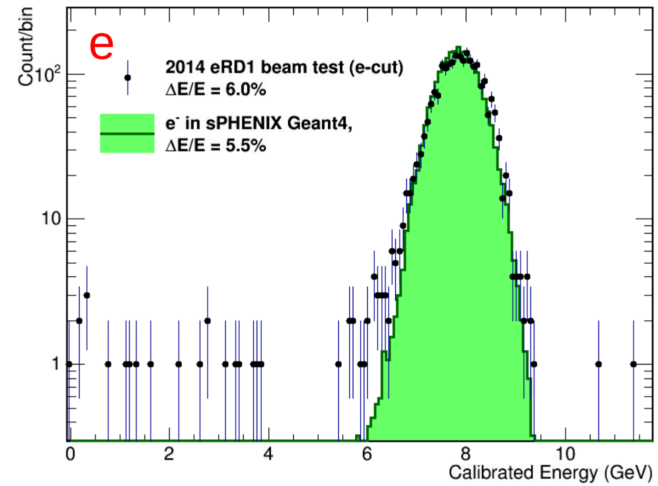


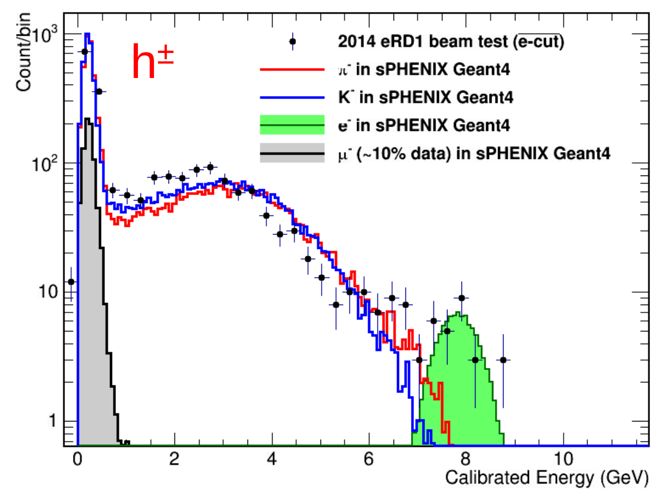
Good agreement !

Will be used to compare with our 2016 test beam results

Compare with expected performance in sPHENIX

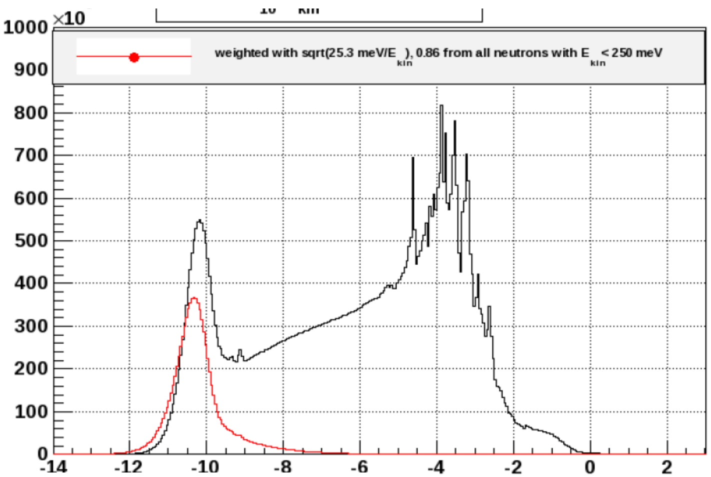
8 GeV





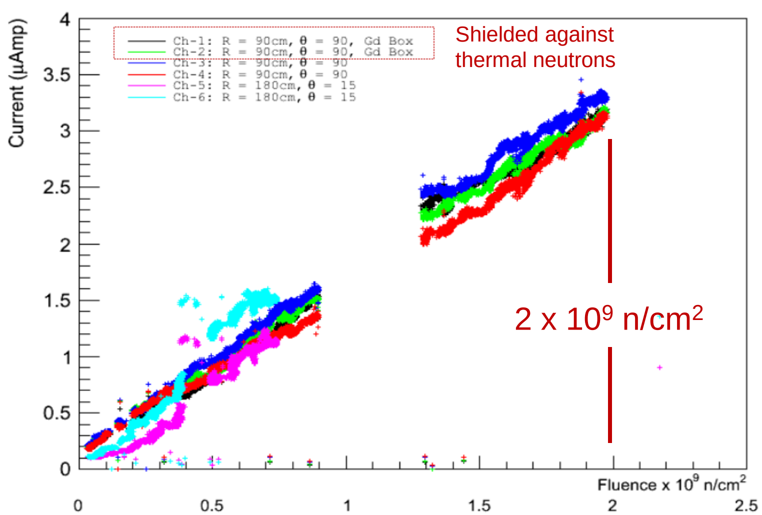
Radiation Damage in SiPMs

Estimated neutron flux in the STAR IR



Y. Fisak et.al. NIM A756 (2014) 68-72

Measured neutron flux in the PHENIX IR



Damage is caused mainly by neutrons (E ~ MeV)

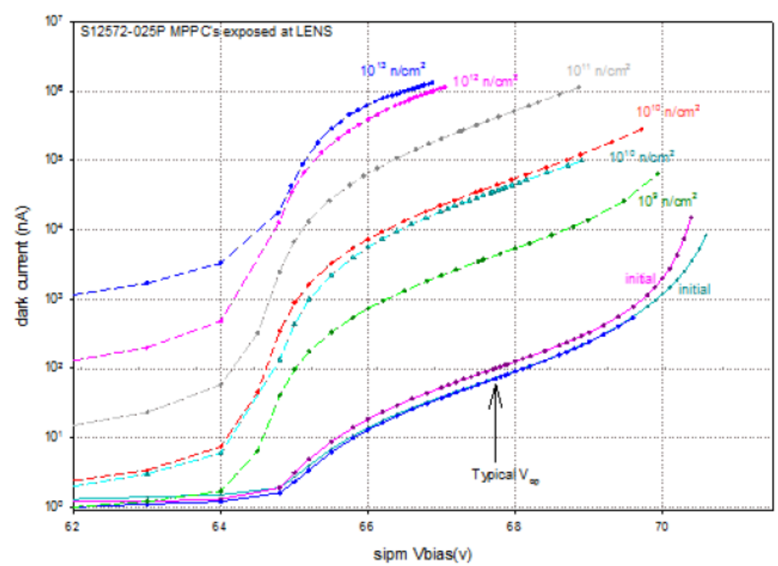
Measure thermal neutron flux in RHIC IR and estimate MeV equivalent neutrons using MC

Estimates in STAR for 2013 run ($L=526\ pb^{-1}$):

$R = 3\text{-}8$ cm, $|Z| < 10$ cm : $\Phi_{eq} \sim 8\times10^{10}\ n/cm^2$

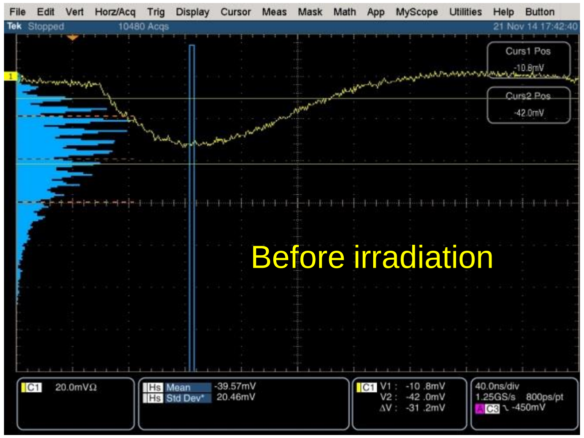
$R = 100$ cm, $Z = 675$ cm : $\Phi_{eq} \sim 2.2\times10^{10}\ n/cm^2$

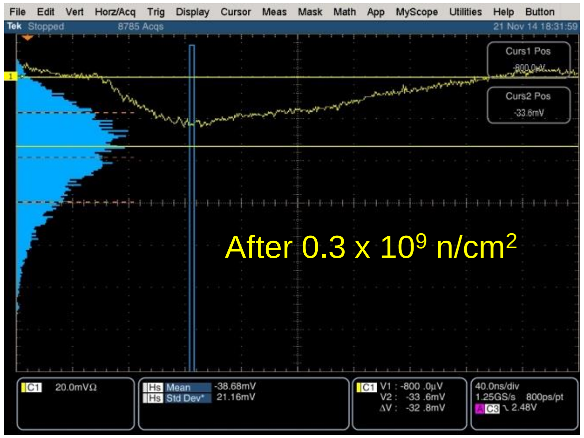
Neutron measurements at the Indiana University LENS Facility



Radiation Damage in SiPMs

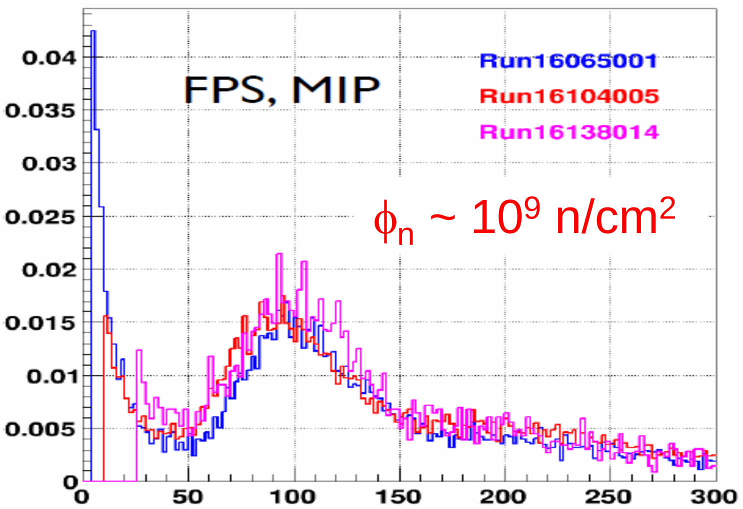
Hamamatsu S12572-025P





Primary effect seems to be increase in noise and not loss of PDE

MIP peak for STAR Forward Preshower detector during RHIC Run 15



O. Tsai, EIC R&D Report, July 2015

Operationally we plan to keep V_b constant for currents up to ~ 1 mA

Will require cooling to maintain ~ 20° C

Comparison of SIC Crystals

Samples	Dimension (mm^3)	LT (%)			LO of 200 ns Gate (p.e./MeV)
		360 nm	440 nm	600 nm	
CMS SIC	22×22×230	21.3	65.6	71.7	10.1
		360 nm	440 nm	600 nm	LO of 200 ns Gate (p.e./MeV)
PANDA B-1757	20×20×200	50.2	71.9	75.1	12.0
PANDA B-1782	20×20×200	49.7	72.0	75.3	13.2
PWO 5	20×20×200	38.6	70.9	75.5	15.6
PWO 7	20×20×200	33.3	66.6	72.0	15.3
PWO 11	20×20×200	28.5	64.7	70.2	12.4
PWO 15	20×20×200	34.1	67.2	72.5	13.0